International
Nuclear
Fuel
Cycle
Evaluation

INFCE

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ECONOMIC ANALYSIS

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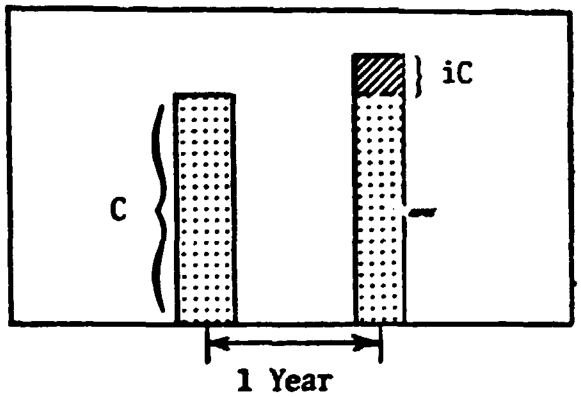
I. Basic Concept of the Time Variability of Money

A. Interest and its relation to present worth

1. Borrowing funds: borrow amount C at the beginning of the year; pay back C plus interest at end of year. Thus,

Payback = $C + iC = C(1+i)$



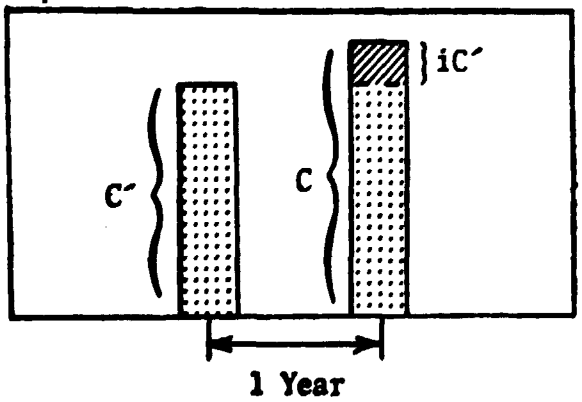
2. Anticipating future expenses: if the expense at the end of the year is amount C, set aside enough money, C′, such that the future expense can be met. Thus, at the end of the year,

Payout = $C' + iC' = C$,

So $C'(1+i) = C$

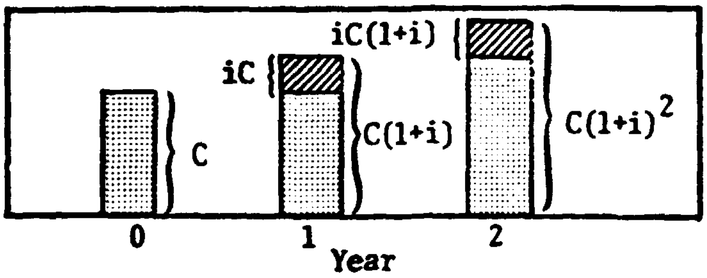
and $C' = \frac{C}{1+i}$

$C' = \frac{C}{1+i}$ may now be described as the present value of a future expense.



3. Extend each of the preceeding examples to more than one year

Borrowing funds:



Year 0: Borrow C

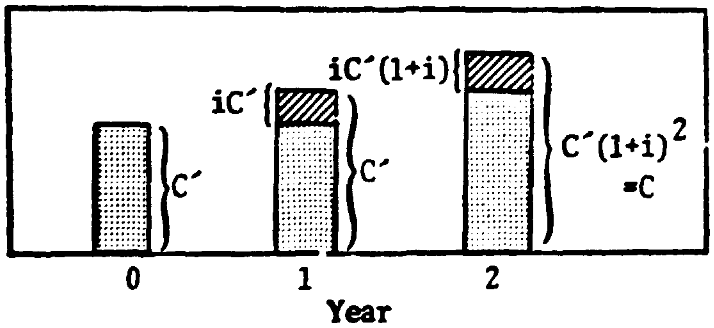
Year 1: Owe amount from previous year plus interest =

$$C + iC = C(1+i)$$

Year 2: Owe amount from previous year plus interest on that amount =

$$C(1+i) + i[C(1+i)] = C(1+i) \times (1+i) = C(1+i)^2, \text{ etc.}$$

Anticipating future expenses:



Year 0: Set aside C´ to meet expense in year 2

Year 1: C´ collects interest and is now worth

$$C' + iC' = C' (1+i)$$

Year 2: The amount from year 1 collects interest and is now worth

$$C' (1+i) + i[C' (1+i)] = C' (1+i)^2$$

But

$$C = C' (1+i)^2,$$

So

$$C' = \frac{C}{(1+i)^2}$$ and this is the present worth of an expense in year 2.

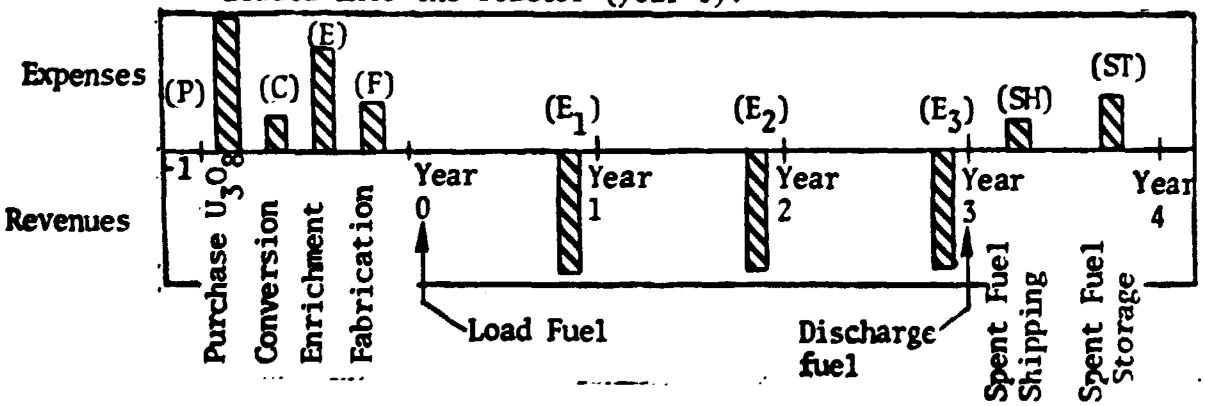
Thus, the present value of any expense (or revenue) C that occurs n years in the future is:

$$\frac{C}{(1+i)^n}$$

We will use the concept of present worth to treat costs that occur throughout the life of a nuclear plant in a systematic manner.

B. Example of present worth treatment of nuclear fuel cycle costs for one batch

Present value all costs to the time at which the fuel is loaded into the reactor (year 0):



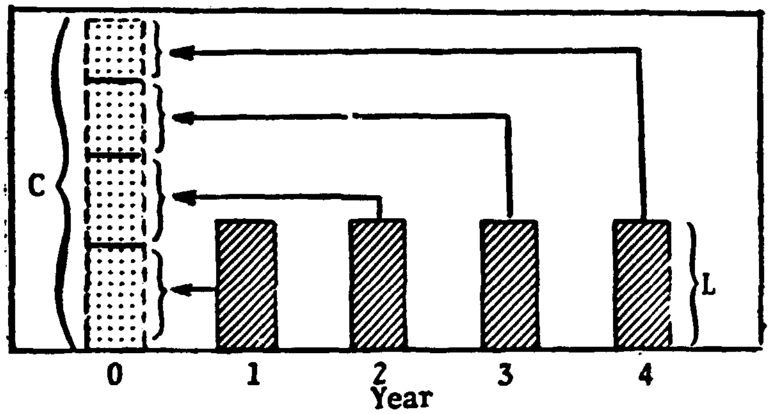
$$\text{Expenses} = P(1+i) + C(1+i) + E(1+i) + F(1+i) + \frac{SH}{(1+i)^4} + \frac{ST}{(1+i)^4}$$

$$\text{Revenues} = \frac{E_1}{1+i} + \frac{E_2}{(1+i)^2} + \frac{E_3}{(1+i)^3}$$

II. Levelized Costs

A. Introduce concept of a levelized cost

A sum of money, C, is borrowed in year 0 and paid back at a constant cost, L, each year such that the debt and its accumulated interest are repaid at the end of the pay-off period.



Although a constant amount, L, is paid out each year, it is worth different amounts when present-valued to year 0. The present worth of the sum of the levelized expenses in the preceeding example is:

$$\frac{L}{(1+i)} + \frac{L}{(1+i)^2} + \frac{L}{(1+i)^3} + \frac{L}{(1+i)^4}$$

This sum may be set equal to the initial investment, C, to obtain an expression for L:

$$C = L\left(\frac{1}{1+i} + \frac{1}{(1+i)^2} + \frac{1}{(1+i)^3} + \frac{1}{(1+i)^4}\right)$$

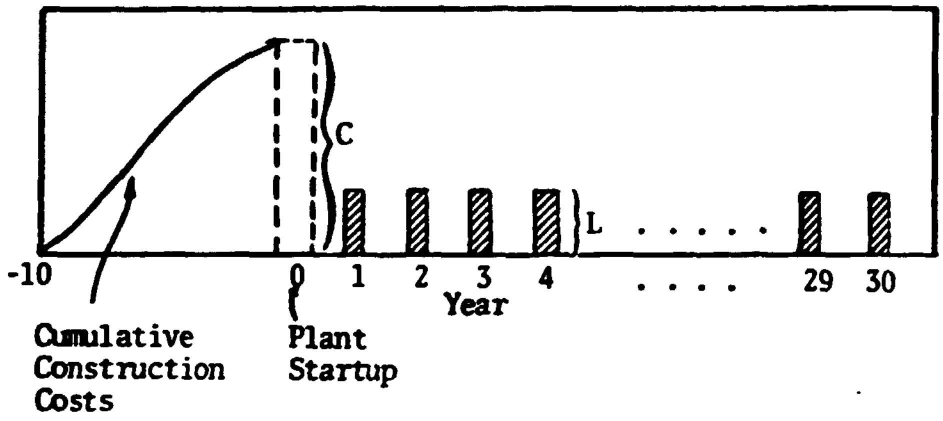
$$L = C/\left(\sum_{k=1}^{4} \frac{1}{(1+i)^k}\right)$$

This may be generalized for a pay-off time of any number of years, K:

$$L = C/\left(\sum_{k=1}^{K} \frac{1}{(1+i)^k}\right)$$

B. Apply to the capital investment in a nuclear plant.

The initial capital costs may be levelized over the full 30-year lifetime of the plant:



III. Capital Payback Methods

A. Discuss debt and equity fractions and rates

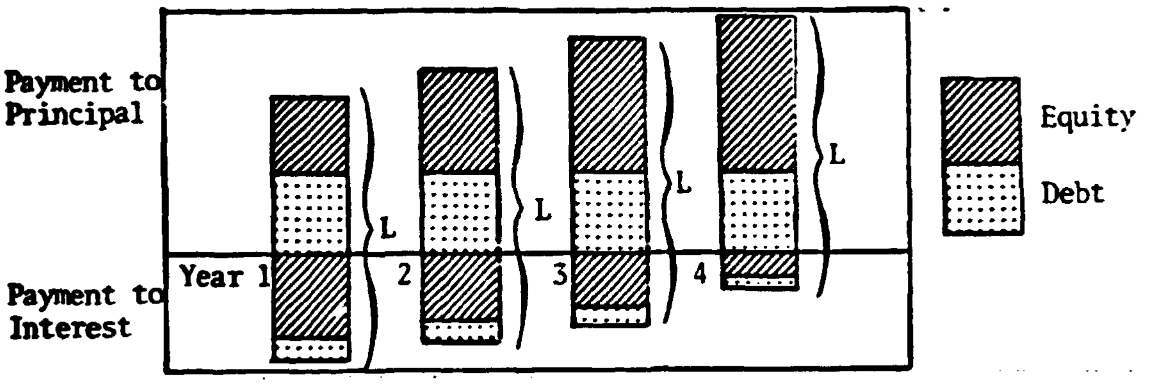
B. Introduce fixed-payment method and proportional method for bond repayment

C. Fixed-payment method

1. The schedule of bond repayment is known in advance and may be in any of the following forms:

- uniform annual reduction of bond principal
- uniform annual payment, including both principal and interest
- any other specified schedule of principal reduction

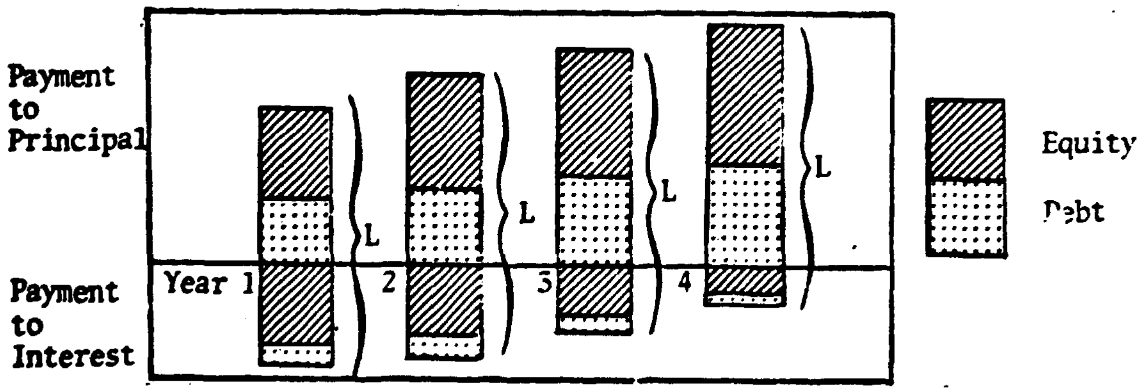
2. The case of the uniform annual reduction of bond principal will be presented. The total capital payment to both debt and equity will be levelized.



Note that the payment to debt principal remains constant as a function of time while the payment to equity principal increases.

D. Proportional Method

1. The initial investment is repaid such that the outstanding bonds and the outstanding equity remain in constant ratio throughout the payback period



Note that the payments to both bond and equity principal increase.

2. Compare the fixed payment and proportional methods and discuss the advantage of each.

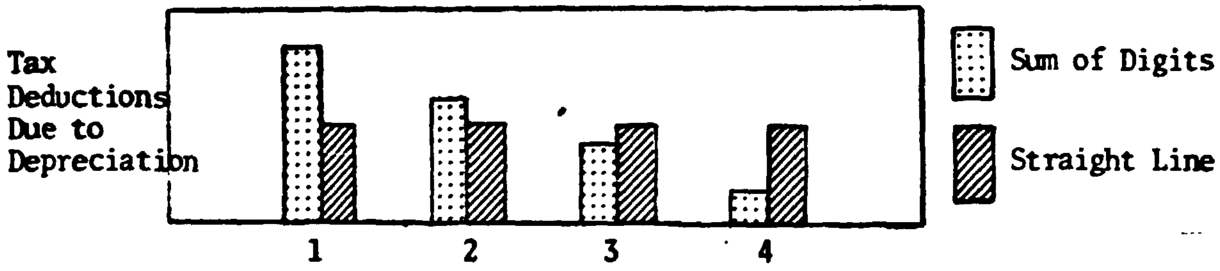
IV. Taxes

A. Discuss general tax laws and rates

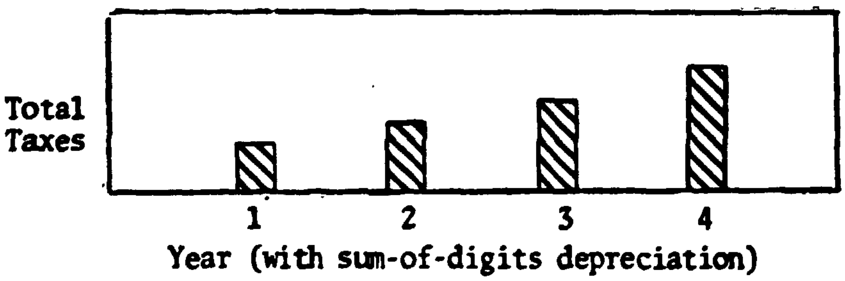
$$\begin{pmatrix}\text{income}\\ \text{taxes}\end{pmatrix} = \begin{pmatrix}\text{tax}\\ \text{rate}\end{pmatrix} \times \left[(\text{revenues}) - \begin{pmatrix}\text{non-fuel}\\ \text{operating}\\ \text{costs}\end{pmatrix} - \begin{pmatrix}\text{bond}\\ \text{interest}\\ \text{payment}\end{pmatrix} - (\text{depreciation})\right]$$

Note that the non-fuel operating expenses consist of fixed charges and operating and maintenance costs; the depreciation term applies to both Capital and fuel.

B. Introduce two methods of depreciating capital items for tax purposes (sum-of-digits and straight line depreciation).

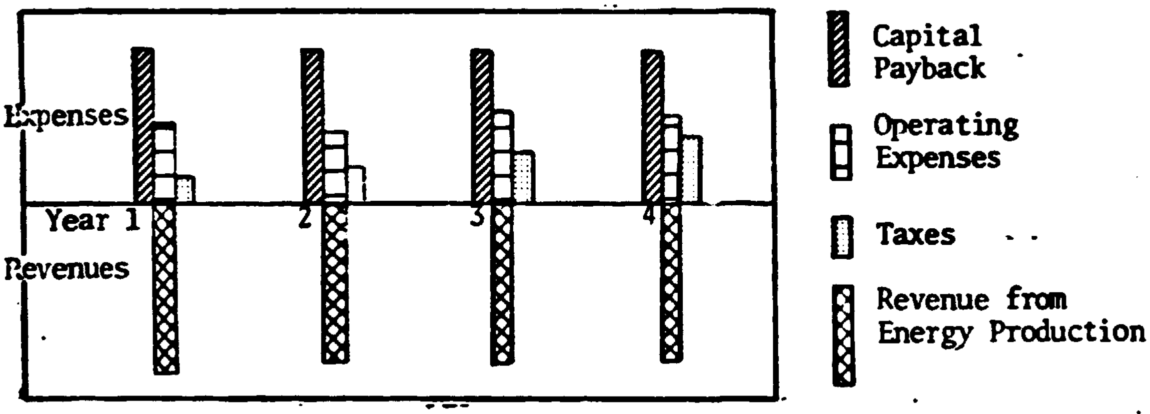


C. General tax trends - note that revenues and operating costs are relatively constant. The tax trends illustrated below include deductions due to bond interest and depreciation.



V. Levelized Total Power Costs

A. Discuss all expense and revenues throughout the lifetime of a plant, using levelized capital costs and taxes from previous sections.



Total Annual Cash Flow

B. Discount all expenses and revenues back to year 0. Require that the sum of all present-valued expenses equal the sum of all present-valued revenues.

C. Revenues in each year are determined by a constant, or "levelized," power cost multiplied by the energy produced in that year.

D. Express the expenses and revenues as follows:

$$\begin{pmatrix}\text{revenues in}\\ \text{any year}\end{pmatrix} = \begin{pmatrix}\text{levelized power}\\ \text{cost}\end{pmatrix} \times (\text{energy produced in that year})$$

$$Rev_k = L \times E_k$$

$$(\text{expenses}) = \begin{pmatrix}\text{payment to}\\ \text{principal}\\ \text{\& interest}\end{pmatrix} + \begin{pmatrix}\text{fixed}\\ \text{charges}\end{pmatrix} + \begin{pmatrix}\text{operating}\\ \text{and}\\ \text{maintenance}\\ \text{costs}\end{pmatrix} + \begin{pmatrix}\text{fuel}\\ \text{cycle}\\ \text{costs}\end{pmatrix} + (\text{income taxes})$$

$$Exp_k = Cap_k + Fix_k + O\&M_k + Fuel_k + Inc_k$$

where $Fuel_k$ represents the fuel expenditure in the year k at the capacity factor of the reactor in that year.

We now require that the sum of all the present-valued revenues equal the sum of all the present-valued expenses.

$$\sum_{k=1}^{K} \frac{Rev_k}{(1+i)^k} = \sum_{k=1}^{K} \frac{Exp_k}{(1+i)^k}$$ where K is the lifetime of the plant

So $$L\sum_{k=1}^{K}\frac{E_k}{(1+i)^k} = \sum_{k=1}^{K}\frac{Cap_k + Fix_k + O\&M_k + Fuel_k + Inc_k}{(1+i)^k}$$

Recall that:

$$\begin{pmatrix}\text{income}\\ \text{taxes}\end{pmatrix} = \begin{pmatrix}\text{tax}\\ \text{rate}\end{pmatrix} \times \left[(\text{revenues}) - \begin{pmatrix}\text{nonfuel}\\ \text{operating}\\ \text{costs}\end{pmatrix} - \begin{pmatrix}\text{bond}\\ \text{interest}\end{pmatrix} - (\text{depreciation})\right]$$

$$Inc_k = t \times \left[L \times E_k - Op_k - Bin_k - Dep_k\right]$$

Also,

$$\begin{pmatrix}\text{nonfuel}\\ \text{operating}\\ \text{costs}\end{pmatrix} = \begin{pmatrix}\text{fixed}\\ \text{charges}\end{pmatrix} + \begin{pmatrix}\text{operating and}\\ \text{maintenance}\\ \text{costs}\end{pmatrix}$$

$$Op_k = Fix_k + O\&M_k$$

And,

$$(\text{depreciation}) = \begin{pmatrix}\text{capital}\\ \text{depreciation}\end{pmatrix} + \begin{pmatrix}\text{fuel}\\ \text{depreciation}\end{pmatrix}$$

$$Dep_k = C\,Dep_k + F\,Dep_k$$

Thus, a new expression for income taxes can be substituted into the equation above:

$$L\sum_{k=1}^{K}\frac{E_k}{(1+i)^k} =$$

$$\sum_{k=1}^{K}\frac{Cap_k + Fix_k + O\&M_k + Fuel_k + t \times (L \times E_k - Fix_k - O\&M_k - Bin_k - C\,Dep_k - F\,Dep_k)}{(1+i)^k}$$

This equation can be rearranged so that we may solve for the levelized power cost, L:

$$L = \frac{\displaystyle\sum_{k=1}^{K}\frac{Cap_k + Fix_k + O\&M_k + Fuel_k - t \times (Fix_k + O\&M_k + Bin_k + C\,Dep_k + F\,Dep_k)}{(1+i)^k}}{\displaystyle(1-t)\sum_{k=1}^{K}\frac{E_k}{(1+i)^k}}$$

The equation may be further developed as follows:

$$L = \frac{\displaystyle\sum_{k=1}^{K} \frac{Cap_k + Fix_k + O\&M_k + Fuel_k + \frac{t}{1-t}(Cap_k + Fuel_k - C\ Bin_k - F\ Bin_k - C\ Dep_k - F\ Dep_k)}{(1+i)^k}}{\displaystyle\sum_{k=1}^{K} \frac{E_k}{(1+i)^k}}$$

The terms may then be separated into several major components of levelized total power cost:

Levelized capital expenses (including associated income taxes and fixed charges)

$$\frac{\displaystyle\sum_{k=1}^{K} \frac{Cap_k + \frac{t}{1-t}(Cap_k - C\ Bin_k - C\ Dep_k) + Fix_k}{(1+i)^k}}{\displaystyle\sum_{k=1}^{K} \frac{E_k}{(1+i)^k}}$$

Levelized operating and maintenance expenses

$$\sum_{k=1}^{K} \frac{\frac{O\&M}{(1+i)^k}}{\displaystyle\sum_{k=1}^{K} \frac{E_k}{(1+i)^k}}$$

Levelized fuel cycle expenses (including associated fuel cycle taxes)

$$\frac{\displaystyle\sum_{k=1}^{K} \frac{Fuel_k + \frac{t}{1-t}(Fuel_k - F\ Bin_k - F\ Dep_k)}{(1+i)^k}}{\displaystyle\sum_{k=1}^{K} \frac{E_k}{(1+i)^k}}$$

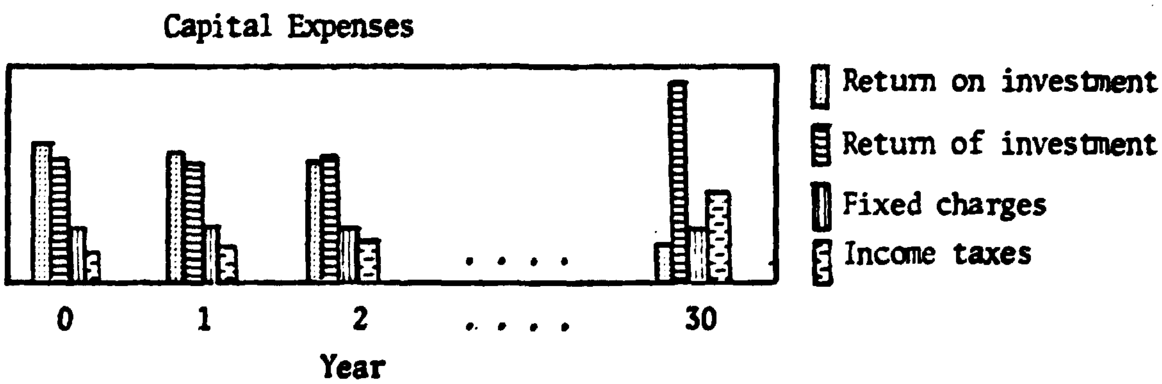
The computer code, HPC, is based on the preceding definition of levelized power costs. This method of calculating power costs is accurate, but involves extensive computation. An alternative method has been developed which involves far less computation, while producing similar results. This will be discussed in the following section.

VI. Approximate method for calculating levelized power costs

A. The three major components of levelized total power cost may be handled in an approximate fashion. The results produced by the approximate method have been shown to agree closely with the results from the accurate HPC treatment.

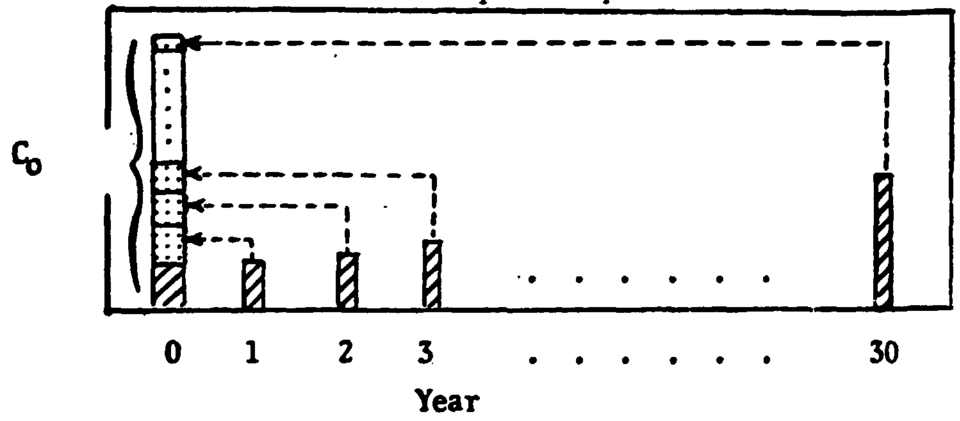
B. Capital Expenses

1. For the purposes of this calculational technique, the capital expenses will include income taxes and fixed charges in addition to the return on and the return of the initial investment.

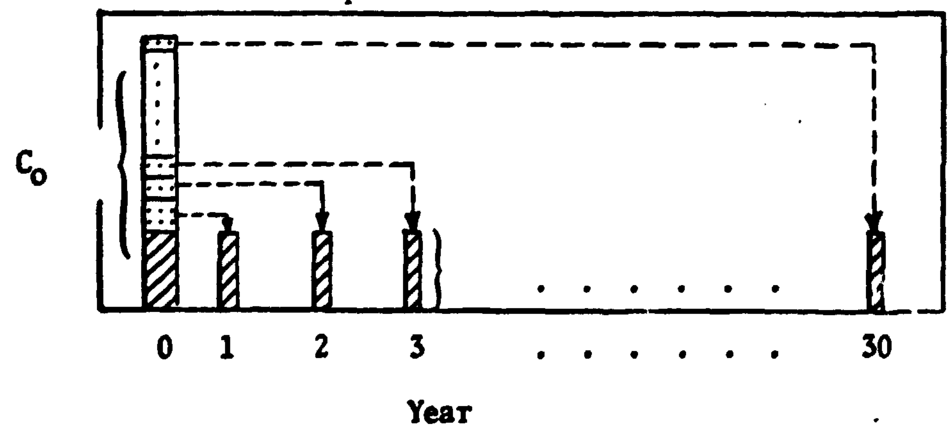


2. In the exact method of calculating the capital cost component, the charges associated with each year were present-valued to the beginning of the first year and then levelized over the lifetime of the reactor.

Present value all capital expenses:



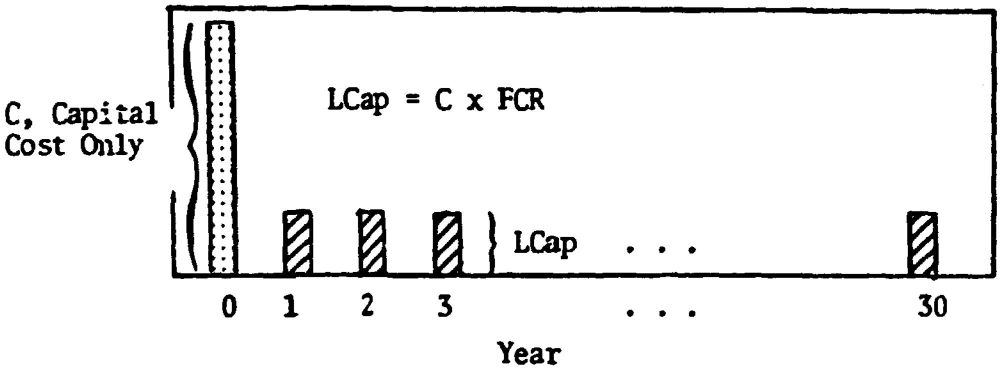
Levelized Capital Costs



3. An alternative procedure for determining the levelized power cost is the fixed-charge-rate method. With this technique, a fixed charge rate is defined such that:

$$\text{(fixed charge rate)} \times \begin{pmatrix}\text{initial capital}\\ \text{investment}\end{pmatrix} = \begin{pmatrix}\text{levelized capital}\\ \text{expenses}\end{pmatrix}$$

$$\text{FCR} \times \text{C} = \text{LCap}$$



4. The annual levelized capital costs may be expressed as:

$$\begin{pmatrix}\text{annual}\\ \text{levelized}\\ \text{capital}\\ \text{expenses}\end{pmatrix} [\text{mills/kwh}] = \frac{\begin{pmatrix}\text{initial}\\ \text{capital}\\ \text{investment}\end{pmatrix} [\$] \times \begin{pmatrix}\text{fixed}\\ \text{charge}\\ \text{rate}\end{pmatrix} [\%/\text{yr}] \times [1000 \text{ mills}/\$]}{\begin{pmatrix}\text{total}\\ \text{energy}\\ \text{produced in}\\ \text{one year}\end{pmatrix} [\text{kwe}] \times [8760 \text{ hrs/yr}]}$$

$$= \frac{\begin{pmatrix}\text{unit capital}\\ \text{cost}\end{pmatrix} [\$/\text{kwe}] \times \begin{pmatrix}\text{installed}\\ \text{capacity}\end{pmatrix} [\text{kwe}] \times \begin{pmatrix}\text{fixed}\\ \text{charge}\\ \text{rate}\end{pmatrix} [\%/\text{yr}] \times [1000 \text{ mill}\$]}{\begin{pmatrix}\text{capacity}\\ \text{factor}\end{pmatrix} \times \begin{pmatrix}\text{installed}\\ \text{capacity}\end{pmatrix} [\text{kwe}] \times [1 \text{ year}] \times [8760 \text{ hrs/yr}]}$$

$$= \frac{\begin{pmatrix}\text{unit capital}\\ \text{cost}\end{pmatrix} [\$/\text{kwe}] \times \begin{pmatrix}\text{fixed charge}\\ \text{rate}\end{pmatrix} [\%/\text{yr}] \times [1000 \text{ mills}/\$]}{\begin{pmatrix}\text{capacity}\\ \text{factor}\end{pmatrix} \times [8760 \text{ hrs/yr}]}$$

or,

$$\text{LCap (mills/kwh)} = \frac{\text{UCap } (\$/\text{kwe}) \times \text{FCR} \times 1000(\text{mills}/\$)}{\text{CF} \times 8760 \text{ hrs}}$$

$$\text{LCap (mills/kwh)} = \frac{\text{UCap x FCR (mills/kwh)}}{\text{CF x 8.760}}$$

C. Operating & Maintenance Costs

1. The operating and maintenance expenses are given as constant annual costs. Thus, the only adjustment that must be made is to convert these costs from \$/kwe-yr to mills/kwh.

2. The operating costs are divided into fixed and variable components. The plant capacity factor must be used to determine the variable operating costs.

3. The levelized operating and maintenance costs may be expressed as:

$$\begin{pmatrix}\text{levelized}\\ \text{operating \&}\\ \text{maintenance}\\ \text{costs}\end{pmatrix} [\text{mills/kwh}]$$

$$= \frac{\begin{pmatrix}\text{O\&M expenses}\\ \text{in one year}\end{pmatrix} [\$/\text{kwe-yr}] \times [1 \text{ year}] \times \begin{pmatrix}\text{installed}\\ \text{capacity}\end{pmatrix} [\text{kwe}] \times [1000 \text{ mills}/\$]}{\begin{pmatrix}\text{total energy}\\ \text{produced in}\\ \text{one year}\end{pmatrix} [\text{kwe-yr}] \times [8760 \text{ hrs/yr}]}$$

$$= \frac{(\text{O\&M expenses}) [\$/\text{kwe-yr}] \times [1 \text{ year}] \times \begin{pmatrix}\text{installed}\\ \text{capacity}\end{pmatrix} [\text{kwe}] \times [1000 \text{ mills}/\$]}{\begin{pmatrix}\text{capacity}\\ \text{factor}\end{pmatrix} \times \begin{pmatrix}\text{installed}\\ \text{capacity}\end{pmatrix} [\text{kwe}] \times [1 \text{ year}] \times [8760 \text{ hrs/yr}]}$$

$$= \frac{(\text{O\&M expenses}) [\$/\text{kwe-yr}] \times [1000 \text{ mills}/\$]}{\begin{pmatrix}\text{capacity}\\ \text{factor}\end{pmatrix} \times [8760 \text{ hrs/yr}]}$$

$$= \frac{\left\{\begin{pmatrix}\text{fixed O\&M}\\ \text{expenses}\end{pmatrix} [\$/\text{kwe-yr}] + \begin{pmatrix}\text{variable}\\ \text{O\&M}\\ \text{expenses}\end{pmatrix} [\$/\text{kwe-yr}] \times \begin{pmatrix}\text{capacity}\\ \text{factor}\end{pmatrix}\right\} \times [1000 \text{ mills}/\$]}{\begin{pmatrix}\text{capacity}\\ \text{factor}\end{pmatrix} \times [8760 \text{ hrs/yr}]}$$

or,

$$\underset{(\text{mills/kwh})}{\text{LO\&M}} = \frac{\left\{\text{FO\&M } (\$/\text{kwe-yr}) + [\text{VO\&M}(\$/\text{kwe-yr}) \times \text{CF}]\right\} \times 1000 \text{ (mills/\$)}}{\text{CF} \times 8760 \text{ (hrs/yr)}}$$

$$\underset{(\text{mills/kwh})}{\text{LO\&M}} = \frac{\text{FO\&M} + (\text{VO\&M} \times \text{CF}) \text{ (mills/kwh)}}{\text{CF} \times 8.76}$$

D. Levelized fuel cycle expenses

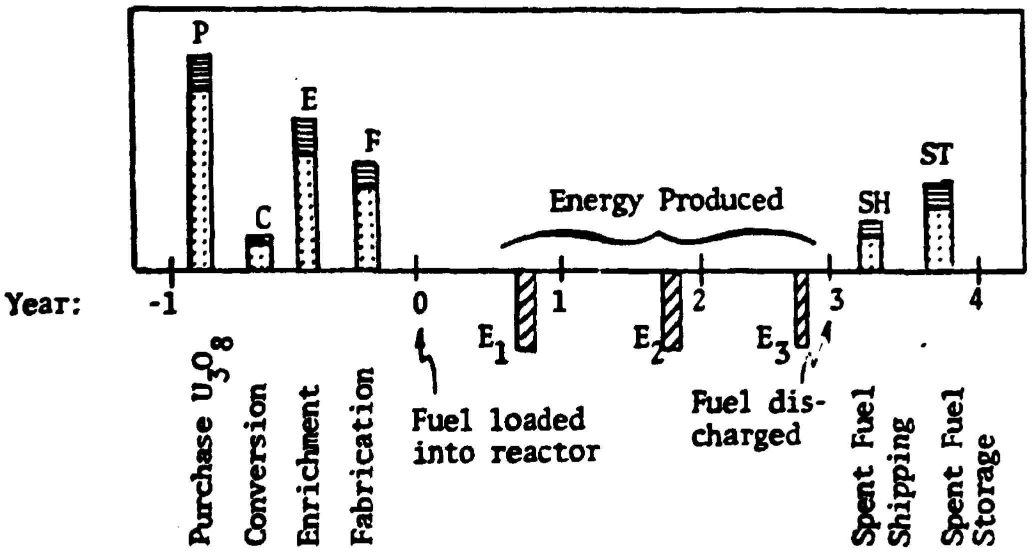
1. In the exact expression for the levelized fuel cycle costs, there was a term involving fuel cycle taxes. This term is difficult to handle in a simplified format. Thus, for the purposes of approximating fuel cycle costs, it was assumed that fuel cycle items were expensed. The tax term then drops out and the levelized fuel cycle component is reduced to:

$$\begin{matrix}\text{Levelized fuel}\\ \text{cycle expenses}\end{matrix} = \frac{\sum_{k=1}^{K} \text{Fuel}_k}{\sum_{k=1}^{K} \frac{E_k}{(1+i)^k}}$$

Recall that Fuel_k is evaluated at the capacity factor of the reactor in the year k and that E_k is the energy production of the reactor in year k. Thus, both $Fuel_k$ and E_k are directly proportional to the annual capacity factor. Consequently, the capacity factor may be eliminated from both terms in this expression. The annual fuel expenses may be evaluated using reactor data at 100% capacity factor if the energy production is also evaluated at a capacity factor of 100%.

2. The approximate technique involves examining a typical batch of fuel. The batch is adjusted such that its costs represent a constant annual fuel expense. One such adjustment involves spreading the additional costs of the first core over all other batches. This is done by an amortization technique as described in a previous section.

3. A typical batch may now be represented as:



The shaded areas added to each fuel cycle component represent adjustments made for additional costs associated with the first and last batches.

The cost associated with each fuel cycle component is determined by the product of the unit cost and the reactor material charge or discharge. For example,

$$\text{Cost of fabrication} = \frac{\$}{\text{kg heavy metal}} \times \frac{\text{kg heavy metal fabricated}}{\text{kwe produced-yr}}$$

The second term represents the kilograms of heavy metal fabricated for one year of power production at a capacity factor of 100%.

4. The expenses associated with an equilibrium batch are all present-valued to the time at which the fuel is loaded into the reactor. If b represents the number of batches in a reactor, the fuel expenses for a batch may be expressed as:

$$\begin{pmatrix}\text{present-} \\ \text{valued} \\ \text{fuel costs} \\ \text{for an} \\ \text{equili-} \\ \text{brium} \\ \text{batch}\end{pmatrix} (\$/\text{kwe-yr}) = P_{eq}(1+i) + C_{eq}(1+i) + E_{eq}(1+i) + F_{eq}(1+i) + \frac{SH_{eq}}{(1+i)^{b+i}} + \frac{ST_{eq}}{(1+i)^{b+1}}$$

The energy production may also be present-valued to the time at which the batch is loaded:

$$\begin{pmatrix}\text{total} \\ \text{present-} \\ \text{valued} \\ \text{energy} \\ \text{produced} \\ \text{by a} \\ \text{batch}\end{pmatrix} (\text{kwe}) = \frac{E_1}{b(1+i)} + \frac{E_2}{b(1+i)^2} + \frac{E_3}{b(1+i)^3} + \ldots + \frac{E_b}{b(1+i)^b}$$

Since the fuel expenditures are evaluated at a capacity factor of 100%, the energy produced is also evaluated at a 100% capacity factor and $E_1 = E_2 = E_3 = \ldots = E_b = E_{100}$.

$$\text{So} \begin{pmatrix} \text{total} \\ \text{present-} \\ \text{valued} \\ \text{energy} \\ \text{produced} \\ \text{by a} \\ \text{batch} \end{pmatrix} \text{(kwe)} = \frac{E_{100}}{b}\left(\frac{1}{1+i} + \frac{1}{(1+i)^2} + \ldots + \frac{1}{(1+i)^b}\right)$$

5. The levelized fuel expenses for an equilibrium cycle may now be expressed as:

$$\begin{pmatrix} \text{levelized} \\ \text{fuel ex-} \\ \text{penses for} \\ \text{an equili-} \\ \text{brium cycle} \end{pmatrix} [\text{mills/kwh}] = \frac{\begin{pmatrix} \text{present-} \\ \text{valued} \\ \text{fuel cost} \\ \text{for an} \\ \text{equilibri-} \\ \text{batch} \end{pmatrix} [\$/\text{kwe-yr}] \times \begin{pmatrix} \text{total} \\ \text{energy} \\ \text{produced} \\ \text{by a} \\ \text{batch} \end{pmatrix} [\text{kwe}] \times [1000 \text{ mills}/\$]}{\begin{pmatrix} \text{total} \\ \text{present-} \\ \text{valued} \\ \text{energy} \\ \text{produced} \\ \text{by a} \\ \text{batch} \end{pmatrix} [\text{kwe}] \times [8760 \text{ hrs/yr}]}$$

or

$$LFuel_{eq} \ [\text{mills/kwh}] = \frac{Fuel_{eq} [\$/\text{kwe-yr}] \times E_{100} \ [\text{kwe}] \times [1000 \text{ mills}/\$]}{\frac{E_{100}}{b}\left(\frac{1}{(1+i)} + \frac{1}{(1+i)^2} + \ldots + \frac{1}{(1+i)^6}\right)[\text{kwe}] \times [8760 \text{ hrs/yr}]}$$

$$= \frac{Fuel_{eq}\ [\$/kwe\text{-}yr] \times [1000\ mills/\$]}{\frac{1}{b}\left(\frac{1}{1+i} + \frac{1}{(1+i)^2} + \cdots + \frac{1}{(1+i)^b}\right) \times [8760\ hrs/yr]}$$

$$LFuel_{eq}\ [mills/kwh] = \frac{Fuel_{eq}}{\frac{1}{b}\left(\frac{1}{1+i} + \frac{1}{(1+i)^2} + \cdots + \frac{1}{(1+i)^b}\right) \times 8.76}\ [mills/kwh]$$

6. The levelized fuel expenses associated with the initial core may also be calculated

   a. Determine the present-valued cost of the first core that is in excess of the present-valued cost of the equilibrium cycle. For example, the excess cost of purchasing U_3O_8 is:

$$\left\{ P_{in} - \left[P_{eq} \times \begin{pmatrix}\text{capacity}\\ \text{factor}\end{pmatrix} \right] \right\} \times (1+i) \quad (\$/kwe)$$

   b. The excess costs due to the first core are then amortized over the 30 years of plant operation:

$$\begin{pmatrix}\text{annual}\\ \text{additional}\\ \text{cost due to}\\ \text{first core}\end{pmatrix} [\$/kwe\text{-}yr] = \begin{pmatrix}\text{total excess}\\ \text{costs due to}\\ \text{first core}\end{pmatrix} \times \left[\frac{i \times (1+i)^{30}}{(1+i)^{30} - 1} \right]$$

   c. The annual additional expense is then expressed in terms of equilibrium batch expenses as:

$$\begin{pmatrix}\text{levelized}\\ \text{additional}\\ \text{expense due}\\ \text{to first core}\end{pmatrix} [mills/kwh] = \frac{\begin{pmatrix}\text{annual}\\ \text{additional}\\ \text{expenses due}\\ \text{to first core}\end{pmatrix} [\$/kwe\text{-}yr] \times \begin{pmatrix}\text{total energy}\\ \text{produced by a}\\ \text{batch}\end{pmatrix} [kwe] \times [1000\ mills/\$]}{\begin{pmatrix}\text{capacity}\\ \text{factor}\end{pmatrix} \times \begin{pmatrix}\text{total present-}\\ \text{valued energy}\\ \text{produced by a}\\ \text{batch}\end{pmatrix} [kwe] \times [8760\ hrs/yr]}$$

$$LFuel_{in} = \frac{Fuel_{in}[\$/kwe] \times E_{100}\ [kwe] \times [1000\ mills/\$]}{CF \times \frac{E_{100}}{b}\left(\frac{1}{1+i} + \frac{1}{(1+i)^2} + \ldots + \frac{1}{(1+i)^b}\right)[kwe] \times [8760\ hrs/yr]}$$

$$= \frac{Fuel_{in}}{\frac{CF}{b} \times \left(\frac{1}{1+i} + \frac{1}{(1+i)^2} + \ldots + \frac{1}{(1+i)^b}\right) \times 8.76}\ [mills/kwh]$$

7. In addition, the levelized fuel expense associated with the final core discharge may be calculated

   a. The excess costs due to the final core discharge are calculated in the same manner as excess costs for the initial core. These costs are then amortized over the 30-years of operation:

$$\left(\begin{array}{l}\text{annual}\\ \text{additional}\\ \text{expenses due}\\ \text{to the last}\\ \text{core}\end{array}\right)[\$/kwe\text{-}yr] = \left(\begin{array}{c}\text{total excess}\\ \text{costs due to}\\ \text{last core}\end{array}\right) \times \frac{1}{(1+i)^{30}} \times \left[\frac{i \times (1+i)^{30}}{(1+i)^{30}-1}\right]$$

   b. Levelized additional expenses due to the last core is handled in the same fashion as the levelized additional expenses due to the first core:

$$LFuel_{final} = \frac{Fuel_{final}}{\frac{CF}{b} \times \left(\frac{1}{1+i} + \frac{1}{(1+i)^2} + \ldots + \frac{1}{(1+i)^b}\right) \times 8.76}\ [mills/kwh]$$

VII. Sample calculation of total power costs using the approximate method.

A. As an illustrative example, the steps in calculating the levelized power costs of a standard LWR on the once-through cycle are shown.

B. Reactor charge and discharge data (given at 100% capacity factor for a plant size of 1000 MWe).

Item	Units	Initial Core	Equilibrium Batch	Final Batch
U_3O_8 charge	Short tons/GWe-yr	376	255	255
Separative work charge	10^3 SWU/GWe-yr	200	153	153
Heavy metal charge	kg/GWe-yr	69073	36458	36458
Heavy metal discharge	kg/GWe/yr	34564	34564	68482

The average annual capacity is 65.9% and the standard LWR has a three-batch core.

C. Economic Data

Discount rate	4.5%/yr
Fixed charge rate	9.8%/yr
Capital cost (including owner's cost and IDC)	770 $/kwe
Operation and maintenance costs	
Fixed component	11.2 $/kwe-yr
Variable component	0.5 $/kwe-yr
U_3O_8 conversion cost	4 $/kg U
Separative work	100 $/SWU

Fabrication	115 \$/kg HM
Spent fuel shipping	20 \$/kg HM
Spent fuel storage	130 \$/kg HM

D. Levelized Capital Expense

$$\text{LCap(mills/kwh)} = \frac{770(\$/\text{kwe}) \times 0.098(\text{fraction/yr}) \times 1000(\text{mills}/\$)}{0.659 \times 8760(\text{hrs/yr})}$$

$$= 13.07 \text{ (mills/kwh)}$$

E. Levelized Operation and Maintenance Expenses

$$\text{LO\&M(mills/kwh)} = \frac{(11.2(\$/\text{kwe-yr}) + 0.5(\$/\text{kwe-yr}) \times 0.659) \times 1000(\text{mills}/\$)}{0.659 \times 8760 \text{ (hrs/yr)}}$$

$$= 2.00 \text{ (mills/kwh)}$$

F. Levelized fuel cycle expenses (assume that the price of U_3O_8 is 40 \$/lb for this example)

1. Levelized fuel cycle expenses associated with an equilibrium batch

a. Present-valued cost of each fuel cycle item

U_3O_8 purchase:

$$P_{eq} \times 1.045 = [255(\text{tons/GWe-yr}) \times 40(\$/\text{lb}) \times 2000(\text{lb/ton})] \times 1.045$$

$$= 21.32 \times 10^6 (\$/\text{GWe-yr}) = 21.32(\$/\text{kwe-yr})$$

U_3O_8 conversion to UF_6:

$$C_{eq} \times 1.045 = [255(\text{tons } U_3O_8/\text{GWe-yr}) \times 4(\$/\text{kg U}) \times 769(\text{kg U/tons } U_3O_8)] \times 1.045$$

$$= 0.82 \times 10^6 (\$/\text{GWe-yr}) = 0.82(\$/\text{kwe-yr})$$

$$E_{eq} \times 1.045 = [153000(\text{SWU/GWe-yr}) \times 100(\$/\text{SWU})] \times 1.045$$

$$= 15.99 \times 10^6(\$/\text{GWe-yr}) = 15.99(\$/\text{kwe-yr})$$

Fabrication:

$$F_{eq} \times 1.045 = [36458(\text{kg HM/GWe-yr}) \times 115(\$/\text{kg HM})] \times 1.045$$

$$= 4.38 \times 10^6(\$/\text{GWe-yr}) = 4.38(\$/\text{kwe-yr})$$

Spent fuel shipping:

$$SH_{eq} \times \frac{1}{(1.045)^4} = [34564(\text{kg HM/GWe-yr}) \times 20(\$/\text{kg HM})] \times \frac{1}{(1.045)^4}$$

$$= 0.58 \times 10^6(\$/\text{GWe-yr}) = 0.58(\$/\text{kwe-yr})$$

Spent fuel storage:

$$ST_{eq} \times \frac{1}{(1.045)^4} = [34564(\text{kg HM/GWe-yr}) \times 130(\$/\text{kg HM})] \times \frac{1}{(1.045)^4}$$

$$= 3.77 \times 10^6(\$/\text{GWe-yr}) = 3.77(\$/\text{kwe-yr})$$

Now the sum of the present-valued fuel costs for an equilibrium batch is:

$$1.045 \times \left(P_{eq} + C_{eq} + E_{eq} + F_{eq}\right) + \frac{\left(SH_{eq} + ST_{eq}\right)}{(1.045)^4} = 46.86(\$/\text{kwe-yr})$$

b. Present-valued energy produced by a batch

For a three-batch core, the present-valued energy produced by a single equilibrium batch at 100% capacity factor is:

$$\frac{1\ \text{GWe}}{3} \times \left[\frac{1}{1.045} + \frac{1}{(1.045)^2} + \frac{1}{(1.045)^3}\right] = 0.92\ \text{GWe}$$

c. The levelized fuel expenses for an equilibrium batch are now:

$$LFuel_{eq} = \frac{46.86(\$/\text{kwe-yr}) \times 1(\text{GWe}) \times 1000(\text{mills}/\$)}{0.92(\text{GWe}) \times 8760\ (\text{hrs/yr})}$$

$$= 5.81\ (\text{mills/kwh})$$

2. Levelized fuel expenses associated with the initial core

   a. Determine present-valued costs associated with the initial core that are in excess of the present-valued costs of an equilibrium cycle.

   The capacity factor of the reactor is 65.9%. Thus, the fuel cycle costs for the equilibrium cycle should be evaluated at 65.9% reactor data.

U_3O_8 purchase:

$$P_{in} \times 1.045 = \{[376-(255 \times 0.659)] \times 40 \times 2000\} \times 1.045$$

$$= 17.39 \text{ (\$/kwe)}$$

U_3O_8 conversion to UF_6:

$$C_{in} \times 1.045 = \{[376-(255 \times 0.659)] \times 4 \times 769\} \times 1.045$$

$$= 0.67 \text{(\$/kwe)}$$

Separative work:

$$E_{in} \times 1.045 = \{[200{,}000 - (153{,}000 \times 0.659)] \times 100\} \times 1.045$$

$$= 10.36 \text{(\$/kwe)}$$

Fabrication:

$$F_{in} \times 1.045 = \{[69073 - (36458 \times 0.659)] \times 115\} \times 1.045$$

$$= 5.41 \text{(\$/kwe)}$$

The sum of the excess fuel cycle costs due to the initial core is:

$$1.045 \times (P_{in} + C_{in} + E_{in} + F_{in}) = 33.83 \text{ (\$/kwe)}$$

b. Amortize the excess costs over the 30 years of plant operation:

$$\begin{pmatrix}\text{annual}\\ \text{additional}\\ \text{cost due to}\\ \text{first core}\end{pmatrix} = 33.83 \times \left[\frac{0.045 \times (1.045)^{30}}{(1.045)^{30}-1}\right]$$

$$= 2.08(\$/\text{kwe-yr})$$

c. The annual expense due to the first core is now:

$$LFuel_{in} = \frac{2.08(\$/\text{kwe-yr}) \times 1(\text{GWe}) \times 1000(\text{mills}/\$)}{0.659 \times 0.92(\text{GWe}) \times 8760(\text{hrs/yr})}$$

$$= .39(\text{mills/kwh})$$

3. Levelized fuel expenses associated with the final core discharge

a. Determine present-valued costs associated with the final core discharge that are in excess of the present-valued costs of an equilibrium cycle.

Spent fuel shipping:

$$SH_{final} \times \frac{1}{(1.045)^4} = \left\{[64842 - (34564 \times 0.659)] \times 20\right\} \times \frac{1}{(1.045)^4}$$

$$= 0.71(\$/\text{kwe})$$

Spent fuel storage:

$$ST_{final} \times \frac{1}{(1.045)^4} = \left\{[64842 - (34564 \times 0.659)] \times 130\right\} \times \frac{1}{(1.045)^4}$$

$$= 4.59(\$/\text{kwe})$$

The sum of the excess fuel cycle costs due to the final core discharge is:

$$\frac{1}{(1.045)^4}\left(SH_{final} + ST_{final}\right) = 5.30(\$/kwe)$$

b. Amortize the excess cost over the 30 years of plant operation:

$$\left(\begin{array}{l}\text{annual} \\ \text{additional} \\ \text{cost due to} \\ \text{last core} \\ \text{discharge}\end{array}\right) = 5.30 \times \frac{1}{(1.045)^{30}} \times \left[\frac{0.045 \times (1.045)^{30}}{(1.045)^{30}-1}\right]$$

$$= 0.09(\$/kwe\text{-}yr)$$

c. The annual expense due to the last core discharge is now:

$$LFuel_{final} = \frac{0.09(\$/kwe\text{-}yr) \times 1(GWe) \times 1000(mills/\$)}{0.659 \times 0.92(GWe) \times 8760(hrs/yr)}$$

$$= 0.02(mills/kwe)$$

4. The total levelized fuel cycle expenses are:

$$LFuel_{in} + LFuel_{eq} + LFuel_{final} = 6.22(mills/kwh)$$

G. The total power cost for the LWR at 40 \$/lb for U_3O_8 is:

$$LCap + LO\&M + LFuel = 21.29(mills/kwh)$$

VIII. Sample calculation of total power cost of an FBR using the approximate method.

A. Reactor charge and discharge data (given at 100% capacity factor for a plant size of 1000 MWe).

Item	Zone	Number of Batches	Initial Core	Equilibrium Batch	Final Batch
Heavy metal charge (kg/GWe-yr)	Core	3	30392	17845	17845
	Axial blanket	3	15357	9017	9017
	Radial blanket	6	27648	6525	6525
Heavy metal discharge (kg/GWe-yr)	Core		17560	17560	30392
	Axial blanket		8871	8871	15357
	Radial blanket		6387	6387	27648

The average annual capacity factor is 65.9%

B. Economic Data

Discount rate	4.5%/yr
Fixed charge rate	9.8%/yr
Capital cost (including owner's cost and TDC at 1.5 times that of the LWR	1155 $/kwe
Operation and maintenance costs	
Fixed component	11.7 $/kwe-yr
Variable component	0.9 $/kwe-yr
Fabrication	
Core	1750 $/kg HM
Axial blanket	35 $/kg HM

Radial blanket	250 \$/kg HM
Total back-end fuel cycle cost (all zones)	570 \$/kg HM

C. Levelized capital expense

$$\text{LCap(mills/kwh)} = \frac{1155(\$/\text{kwe}) \times 0.098(\text{fraction/yr}) \times (1000 \text{ mills/\$})}{0.659 \times 8760 \text{ (hrs/yr)}}$$

$$= 19.61 \text{ (mills/kwh)}$$

D. Levelized operation and maintenance expenses

$$\text{LO\&M(mills/kwh} = \frac{(11.7(\$/\text{kwe-yr}) + 0.9(\$/\text{kwe-yr}) \times 0.659) \times 1000(\text{mills/\$})}{0.659 \times 8760 \text{ (hrs/yr)}}$$

$$= 2.13(\text{mills/kwh})$$

E. Levelized fuel cycle expenses

1. Levelized fuel cycle expenses associated with an equilibrium batch

   a. Present-valued cost of each fuel cycle item

Fabrication:

$$F_{eq} \times 1.045 = (17845 \text{ (kg/ HM/GWe-yr)} \times 1750 \text{ (\$/kg HM)} \times 1.045 \quad \text{(core)}$$

$$+ (9017 \text{ (kg HM/GWe-yr)} \times 35 \text{ (\$/kg HM)}) \times 1.045 \quad \text{(axial blanket)}$$

$$+ (6525 \text{ (kg HM/GWe-yr)} \times 250 \text{ (\$/kg HM)}) \times 1.045 \quad \text{(radial blanket)}$$

$$= 34.67 \times 10^6 \text{ (\$/GWe-yr)} = 34.67 \text{ (\$/kwe-yr)}$$

Total back-end costs for core + axial blanket:

$$B_{eq}(\text{core+AB}) \times \frac{1}{(1.045)^4} = (17560 \text{ (kg HM/GWe-yr)} \times 570 \text{ (\$/kg HM)}) \times \frac{1}{(1.045)^4} \quad \text{(core)}$$

$$+ (8871 \text{ (kg HM/GWe-yr)} \times 570 \text{ (\$/kg HM)}) \times \frac{1}{(1.045)^4} \quad \text{(axial blanket)}$$

$$= 12.63 \times 10^6 \text{ (\$/GWe-yr)} = 12.63 \text{ (\$/kwe-yr)}$$

Total back-end costs for the radial blanket:

$$B_{eq}(RB) \times \frac{1}{(1.045)^7} = (6387 \text{ (kg HM/GWe-yr)} \times 570 \text{ (\$/kg HM)}) \times \frac{1}{(1.045)^7}$$

$$= 2.68 \times 10^6 \text{ (\$/GWe-yr)} = 2.68 \text{ (\$/kwe-yr)}$$

Now the sum of the present-valued fuel costs for an equilibrium batch is:

$$F_{eq} \times 1.045 + B_{eq}(\text{core+AB}) \times \frac{1}{(1.045)^4} + B_{eq}(RB) \times \frac{1}{(1.045)^7} = 49.98 \text{ (\$/kwe-yr)}$$

b. The present valued energy produced by a batch at 100% capacity factor is:

$$\frac{1 \text{ GWe}}{3} \times \left[\frac{1}{1.045} + \frac{1}{(1.045)^2} + \frac{1}{(1.045)^3}\right] = 0.92 \text{ GWe}$$

c. The levelized fuel expenses for an equilibrium batch are now:

$$LFuel_{eq} = \frac{49.98 \text{ (\$/kwe-yr)} \times 1 \text{ (GWe)} \times 1000 \text{ (mills/\$)}}{0.92 \text{ (GWe)} \times 8760 \text{ (hrs/yr)}}$$

$$= 6.20 \text{ (mills/kwh)}$$

2. Levelized fuel expenses associated with the initial core

a. Present-valued costs of the initial core that are in excess of the present-valued costs of an equilibrium batch

Fabrication:

$$F_{in} \times 1.045 = ((30392 - (17845 \times 0.659)) \times 1750) \times 1.045 \quad \text{(core)}$$

$$+ ((15357 - (9017 \times 0.659)) \times 35) \times 1.045 \quad \text{(axial blanket)}$$

$$+ ((27648 - (6525 \times 0.659)) \times 250) \times 1.045 \quad \text{(radial blanket)}$$

$$= 40.52 \text{ (\$/kwe)}$$

b. Amortize the excess costs over the 30 years of plant operation:

$$\begin{pmatrix}\text{annual} \\ \text{additional} \\ \text{cost due to} \\ \text{first core}\end{pmatrix} = 40.52 \times \left[\frac{0.045 \times (1.045)^{30}}{(1.045)^{30} - 1}\right]$$

$$= 2.49 \ (\$/\text{kwe-yr})$$

c. The annual expense due to the first core is now:

$$LFuel_{in} = \frac{2.49 \ (\$/\text{kwe-yr}) \times 1 \ (\text{GWe}) \times 1000 \ (\text{mills}/\$)}{0.659 \times 0.92 \ (\text{GWe}) \times 8760 \ (\text{hrs/yr})}$$

$$= 0.47 \ (\text{mills/kwh})$$

3. Levelized fuel expenses associated with the final core discharge

a. Present-valued costs of the final core that are in excess of the present-valued costs of an equilibrium batch.

Total back-end costs for the core + axial blanket:

$$B_{final}(\text{core+AB}) \times \frac{1}{(1.045)^4} = ((30392 - (17560 \times 0.659)) \times 570) \times \frac{1}{(1.045)^4} \ (\text{core})$$

$$+ ((15357 - (8871 \times 0.659)) \times 570) \times \frac{1}{(1.045)^4} \ (\text{axial blanket})$$

$$= 13.54 \ (\$/\text{kwe})$$

Total back-end costs for the radial blanket:

$$B_{final}(\text{RB}) \times \frac{1}{(1.045)^7} = ((27648 - (6387 \times 0.659)) \times 570) \times \frac{1}{(1.045)^7}$$

$$= 9.82 \ (\$/\text{kwe})$$

The sum of the excess fuel cycle costs due to the final core discharge is 23.36 ($/kwe)

b. Amortize the excess cost over the 30 years of plant operation:

$$\begin{pmatrix}\text{annual}\\ \text{additional}\\ \text{cost due to}\\ \text{final core}\\ \text{discharge}\end{pmatrix} = 23.36 \times \frac{1}{(1.045)^{30}} \times \left[\frac{0.045 \times (1.045)^{30}}{(1.045)^{30} - 1}\right]$$

$$= 0.38\ (\$/\text{kwe-yr})$$

c. The annual expense due to the last core discharge is now:

$$LFuel_{final} = \frac{0.38\ (\$\text{kwe-yr}) \times 1\ (\text{GWe}) \times 1000\ (\text{mills}/\$)}{0.659 \times 0.92\ (\text{GWe}) \times 8760\ (\text{hrs/yr})}$$

$$= 0.07\ (\text{mills/kwh})$$

4. The total levelized fuel cycle expenses are:

$$LFuel_{in} + LFuel_{eq} + LFuel_{final} = 6.74\ (\text{mills/kwh})$$

F. The total power cost for the FBR at a capital cost of 1.5 times that of the LWR is:

LCap + LO&M + LFuel = 28.48 (mills/kwh)